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WIND–STRUCTURE INTERACTION ON CONSTRUCTION STAGES FOR UNBALANCED SEGMENTAL BRIGDES

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Abstract. Behavior due to wind–structure interaction of segmental bridges on construction stages is presented. The paper deals with the analysis of the bridge “Viaducto km 61+000” located near the city of Xalapa, in the state of Veracruz, Mexico. This 470 m long bridge with 17.9 m wide cast in place box girder will carry four lanes of traffic over a deep valley, with piers height from 26 m to 113 m. The superstructure consists of two central spans of 145 m long and two approach spans of 90 m long. The roadway geometry has vertical and horizontal curvatures along the entire length of the bridge. The substructure consists of cast–in–place rectangular hollow piers on bored pile foundations and spread footings. The superstructure is erected by the unbalanced cantilever method using form travelers. Computational fluid dynamics based on the finite element method is used to simulate wind forces acting on the structure, which are coupled to computational structure dynamics on construction stages. Thus, a stabilized fluid flow formulation is presented together with an ALE scheme while geometrically non–linear solid dynamics finite elements are used to simulate the bridge behavior. Both solutions are coupled together using a strong coupling technique to perform an aeroelastic analysis of the bridge. Differences obtained among numerical approach and code requirements are presented.

1 INTRODUCTION

On construction stages, most of civil constructions are vulnerable to nature acting forces like wind or earthquakes, in the specific case of bridges, forces are resisted in one or two places at most on construction stages, making a very vulnerable structure and needing a careful construction process. A good behavior estimate on construction stages permit to achieve a successful constructions without undesirable incidents.

“Viaducto km 61+000” is a 470 m long bridge now in construction with two central spans of 145 m and two approach spans of 90 m. Figure 1 shows a view of bridge when it will be finished. The superstructure is supported by three cast–in–place rectangular hollow piers from 26 m to 113 m height on bored pile foundations and spread footings.

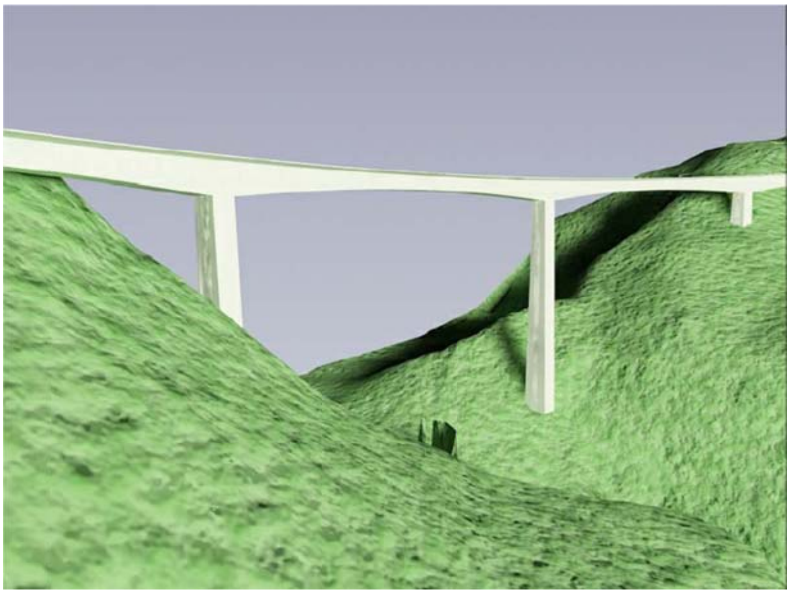

Figure 1 Simulated bridge view when it will be finished

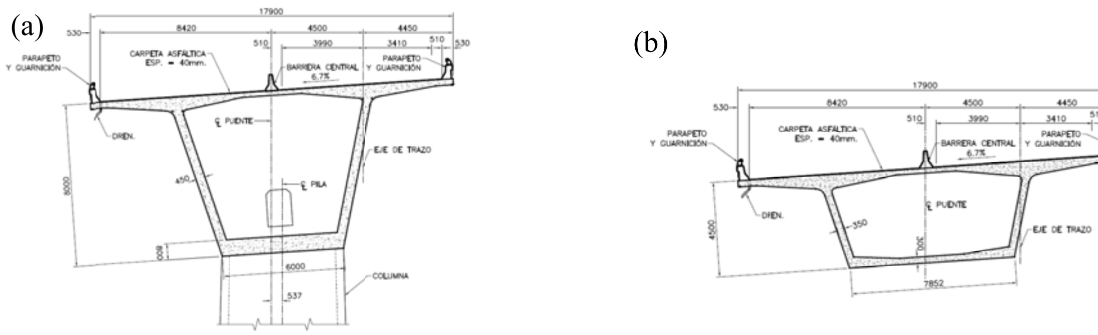

Figure 2 Superstructure section geometry (a) Pile segment (b) Mid central span

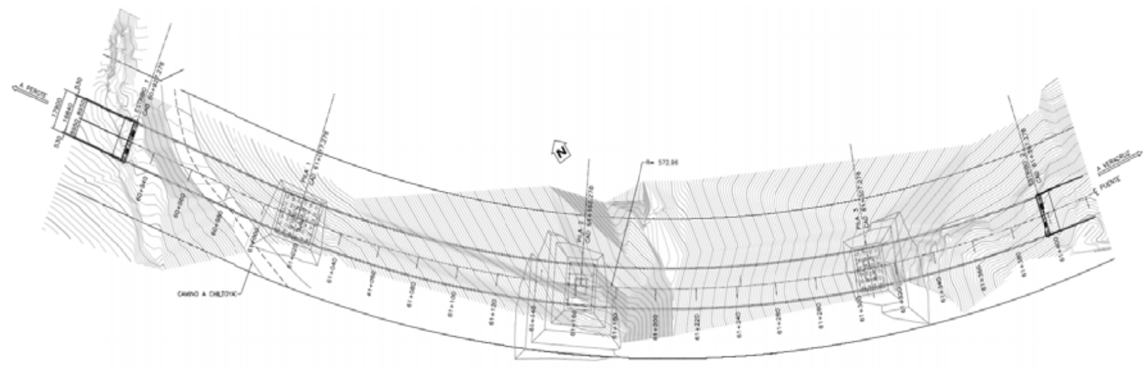

Figure 3 Bridge plan view

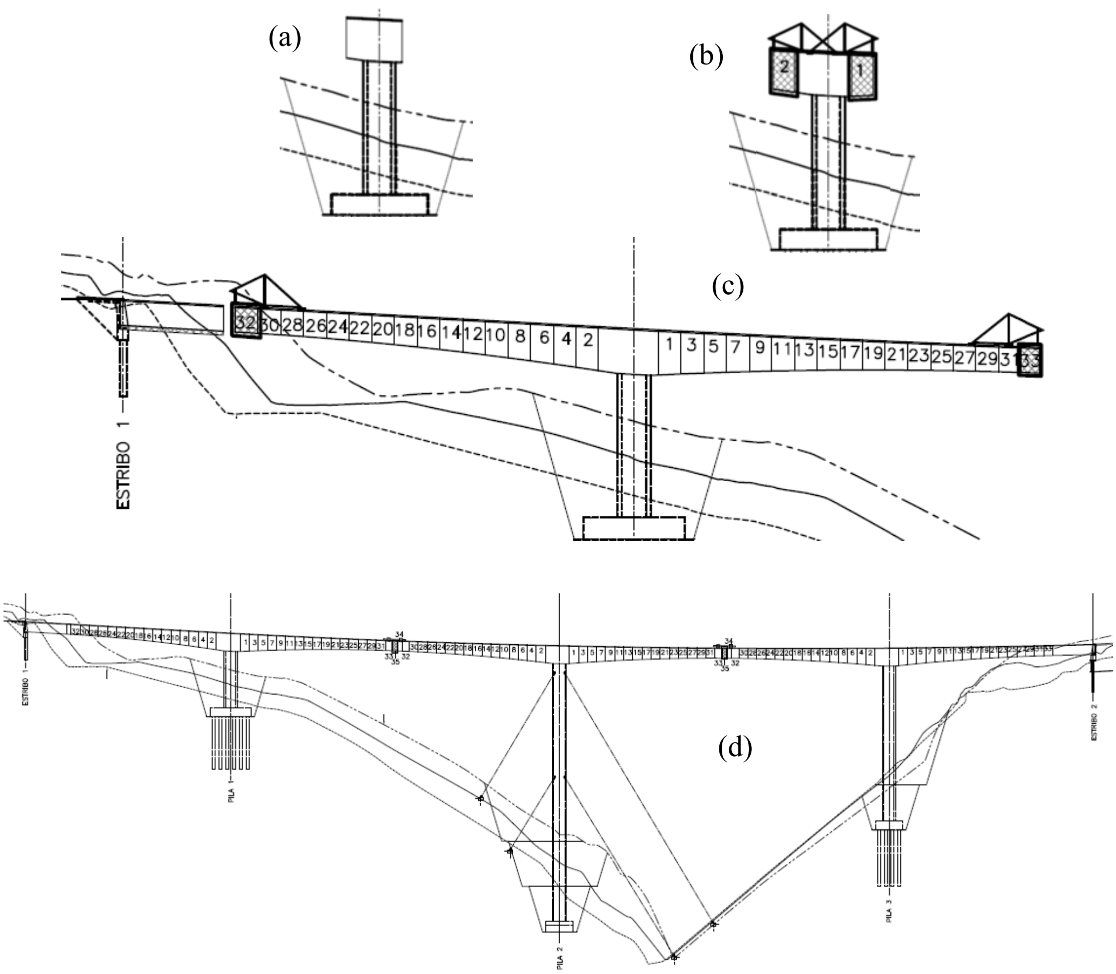

Figure 4 Description of some bridge construction stages (a) Construction of pile and pile segment (b) Form travelers colocation on pile segment (c) Segments construction sequence in cantilever (d) Construction of closure segments

The superstructure is a 17.9 m wide cast–in–place box girder with variable section (see Figure 2) and will carry four lanes of traffic. The roadway has vertical and horizontal curvature along the entire length of the bridge as can be showed in Figure 3 and Figure 4(d). Superstructure construction procedure consists of use two form travelers in unbalanced cantilever above each pile, which is described in Figure 4. Before construct closure segments are placed, bridge substructures are isostatic inverted pendulums, which are very vulnerable to nature forces like wind or earthquakes.

In this paper finite element analysis considering wind–structure interaction at some construction stages is presented. Acting forces obtained from code requirements [1] and finite element analysis considering wind–structure interaction are compared.

3 FLUID–STRUCTURE MODELATION

3.1 Structure

For structural purposes, a geometrically nonlinear solid analysis is employed. Mathematical expressions to solve the structural part are obtained from lineal momentum conservation equation, once discretized with finite elements consists of solve the next equation

$$\mathbf{f}^{\text{int}}\left(\mathbf{u}_{n+1}\right)+\mathbf{M}\ddot{\mathbf{u}}_{n+1}=\mathbf{f}^{\text{ext}}\left(\mathbf{u}_{n+1}\right) \tag{1}$$

where

$\mathbf{f}^{\text{int}}$ =Internal forces
$\mathbf{f}^{\text{ext}}$ = External forces
$\mathbf{M}$ = Mass
$\mathbf{u}$ = Displacements vector
$\ddot{\mathbf{u}}$ = Acceleration field

Generalized–α method is used to compute time integration for equation (1) because other traditional methods like β–Newmark technique produce spurious results with geometrically nonlinear finite element analysis.

Figure 5 shows a 3D–view of the structural model to be used to compute the dynamic of the structure due to wind action.

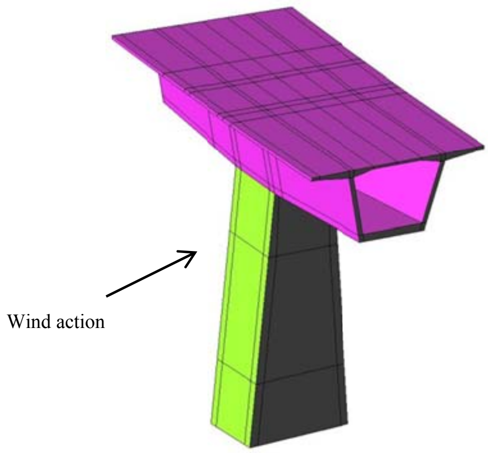

Figure 5 Structure model to compute structural dynamic system

3.2 Fluid

An incompressible fluid formulation has been used to simulate wind action due to wind velocity is lower than 0.3 Mach. Navier–Stokes equations are used to model fluid flow expressed as

$$\mathbf{M}\dot{\mathbf{v}}_{n+1} + \mathbf{K}\mathbf{v}_{n+1} - \mathbf{G}\mathbf{p}_{n+1} = \mathbf{f}_{n+1}^{\mathrm{ext}} \qquad (2)$$
$$\mathbf{G}^T\mathbf{v}_{n+1} = 0$$

where

$\mathbf{v}$ = Velocity
$\mathbf{p}$ = Pressure field
$\dot{\mathbf{v}}$ = Acceleration
$\mathbf{M}$ = Mass matrix
$\mathbf{K}$ = Matrix with convective and viscous terms
$\mathbf{G}$ = Matrix to include pressure terms or to consider the incompressibility fluid

For dynamic fluid flow analysis, equations (2) can be expressed as

$$\left(\boldsymbol{v}_h^{n+1}, \boldsymbol{w}_h\right) + c\left(\boldsymbol{v}_h^{n+1}, \boldsymbol{v}_h^{n+1}, \boldsymbol{w}_h\right) - b\left(p^{n+1}, \boldsymbol{w}_h\right) + a\left(\boldsymbol{v}_h^{n+1}, \boldsymbol{w}_h\right) = \left(\boldsymbol{b}_h^{n+1}, \boldsymbol{w}_h\right) \qquad (3)$$
$$b\left(q_h, \boldsymbol{v}_h^{n+1}\right) = 0$$

In the equation (3) notation used in [2] and [3] has been employed and the meaning can be founded in [4]. To analyze the structure in a faster way, equations (3) has been uncoupled using fractional step method that can be founded in [3], and considering this expressions are fully eulerian, an ALE formulation has been used to take in count the structure movement and move the domain fluid as well. The uncoupled equations are expressed as

$$\left(\dot{\tilde{\boldsymbol{u}}}_h^{n+\alpha_m^{\mathrm{f}}}, \boldsymbol{w}_h\right) + c\left(\tilde{\boldsymbol{c}}_h^{n+\alpha_f^{\mathrm{f}}}, \tilde{\boldsymbol{v}}_h^{n+\alpha_f^{\mathrm{f}}}, \boldsymbol{w}_h\right) - b\left(p_h^n, \boldsymbol{w}_h\right) + a\left(\tilde{\boldsymbol{v}}_h^{n+\alpha_f^{\mathrm{f}}}, \boldsymbol{w}_h\right) +$$
$$\tau\left(\tilde{\boldsymbol{c}}_h^{n+\alpha_f^{\mathrm{f}}} \cdot \nabla\tilde{\boldsymbol{v}}_h^{n+\alpha_f^{\mathrm{f}}} + \nabla p_h^n - \pi_h^n, \tilde{\boldsymbol{c}}_h^{n+\alpha_f^{\mathrm{f}}} \cdot \nabla\boldsymbol{w}_h\right) = \left(\boldsymbol{b}_h^{n+1}, \boldsymbol{w}_h\right)$$
$$-\frac{\Delta t\, \gamma^{\mathrm{f}}}{\alpha_m^{\mathrm{f}}}\left(\nabla\left[p_h^{n+1} - p_h^n\right], \nabla q_h\right) - \tau\left(\tilde{\boldsymbol{c}}_h^{n+\alpha_f^{\mathrm{f}}} \cdot \nabla\tilde{\boldsymbol{v}}_h^{n+\alpha_f^{\mathrm{f}}} + \nabla p_h^{n+1} - \pi_h^n, \nabla q_h\right) = b\left(q_h, \tilde{\boldsymbol{v}}_h^{n+1}\right) \qquad (4)$$
$$\frac{\alpha_m^{\mathrm{f}}}{\Delta t\, \gamma^{\mathrm{f}}}\left(v_h^{n+1} - \tilde{\boldsymbol{v}}_h^{n+1}, w_h\right) - b\left(p_h^{n+1} - p_h^n, \boldsymbol{w}_h\right) = 0$$
$$\left(\pi_h^{n+1}, \eta_h\right) - \left(\tilde{\boldsymbol{c}}_h^{n+\alpha_f^{\mathrm{f}}} \cdot \nabla\tilde{\boldsymbol{v}}_h^{n+\alpha_f^{\mathrm{f}}} + \nabla p_h^{n+1}, \eta_h\right) = 0$$

Equations (4) are formulated in a four implicit steps for each time step. The first step consists of solve system at an intermediate velocity, which is a nonlinear formulation. Once found the intermediate velocity, in the second step the final pressure is computed. Final velocity is calculated in third step, and finally, the complete system is stabilized in the fourth step. The generalized–α method is used for time integration of the fractionated step. A complete analytical deduction of generalized–α method can be founded for incompressible fluids in [4].

Figure 6 shows a view of used mesh to compute fluid flow around the structure, where structure model (Figure 5) fits exactly.

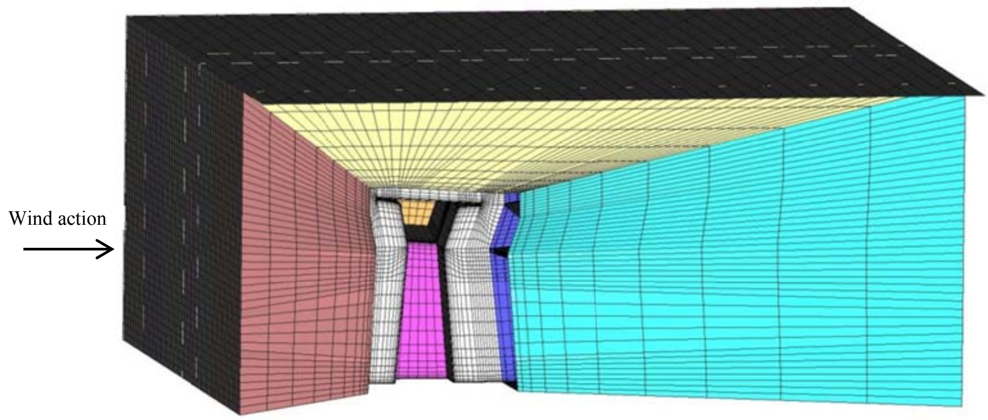

Figure 6 Internal mesh used to compute fluid flow around the structure

3.3 Fluid–structure interaction

Structure and the fluid are solved in a domain that contains the structure; both calculations are employed to predict the simultaneous effects, solving fluid and structure at the same time like in real world. The couple fluid–structure interaction problem can be performed using a monolithic solution [5] or partitioned scheme [6], [4].

Principal disadvantages of monolithic solutions are related to have all programmed in one code, adding the problem of increase the degrees of freedom, and for hence, computational time. Partitioned methods permit to have specialized codes to each part of the problem, in this case, structure and fluid codes. Having separated codes permit to reduce computational time to achieve solution. Disadvantage of partitioned approach is related to convergence of coupling solutions, which can be solved employing Aitken schemes that solve the coupling for problems where the added mass effect is not significant. This solution is used in [4] giving great result for aeroelastic problems like treated in [7] and is used for problem herein presented.

Calculus process consists of predict displacements of structure using the structural solver (CSD) considering the structural dynamic response of the previous time step. Then the displacement predictions of the structure are passed to the mesh solver (CMD) to match the fluid mesh with deformed structure. When fluid mesh is adjusted, a fluid solver (CFD) is used to compute the dynamic fluid flow. Finally acting fluid forces on structure are passed to structural solver to update structure displacements. This depicted procedure is computed until convergence criteria is achieved, ending the time step. Algorithms for coupling calculations can be founded in [4].

4 STUDIED PROBLEM

In this paper, construction above Pile 1 is presented (see Figure 4) focusing in results obtained for FSI after construct the fifth superstructure segment. Figure 5 shows the finite element model used to compute structural dynamics of the bridge. Mesh used to simulate wind action on structure is showed in Figure 6 when the place occupied by the structure can be seen inside.

Wind action is established using requirements specified by the Mexican Federal Electric Commission Code, *(Comisión Federal de Electricidad, CFE)* [8], which is the code applicable in Mexico for wind design at the construction site. Wind velocity profile for analysis is showed in Figure 7.

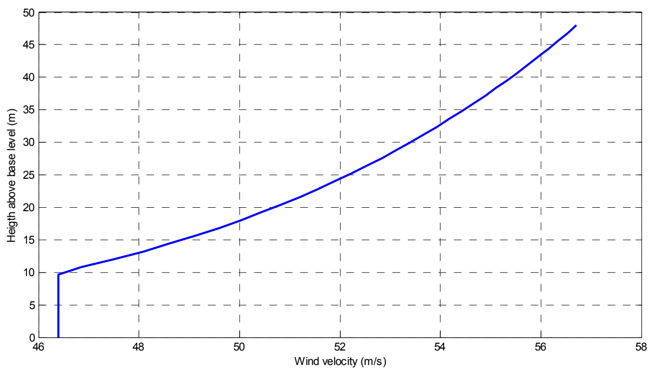

Figure 7 Wind velocity profile for analysis

Figure 8 shows wind pressure and structure deformation at several time steps for one complete vibration cycle, representing the dynamic behavior of the structure. Moreover Figure 9 shows the fluid state at one time step around the structure. At the scale showed in Figure 9 structure deformation cannot be appreciated, but it is considered.

Table 1 shows some results obtained from code regulations established in [1] and [9] corresponding to a static analysis and compared to FSI analysis described in this paper. As can be seen, obtained displacements at the top of the structure are greater with FSI than code requirements. Shear forces and overturning moments computed at pile base have a lower value with FSI compared to code analysis. The results shows that even displacement predictions with FSI are greater, forces are not, this is because the static analysis is not enough to predict inertial forces acting in the structure, but conservative forces considered in in the static analysis results in greater reactions at pile base.

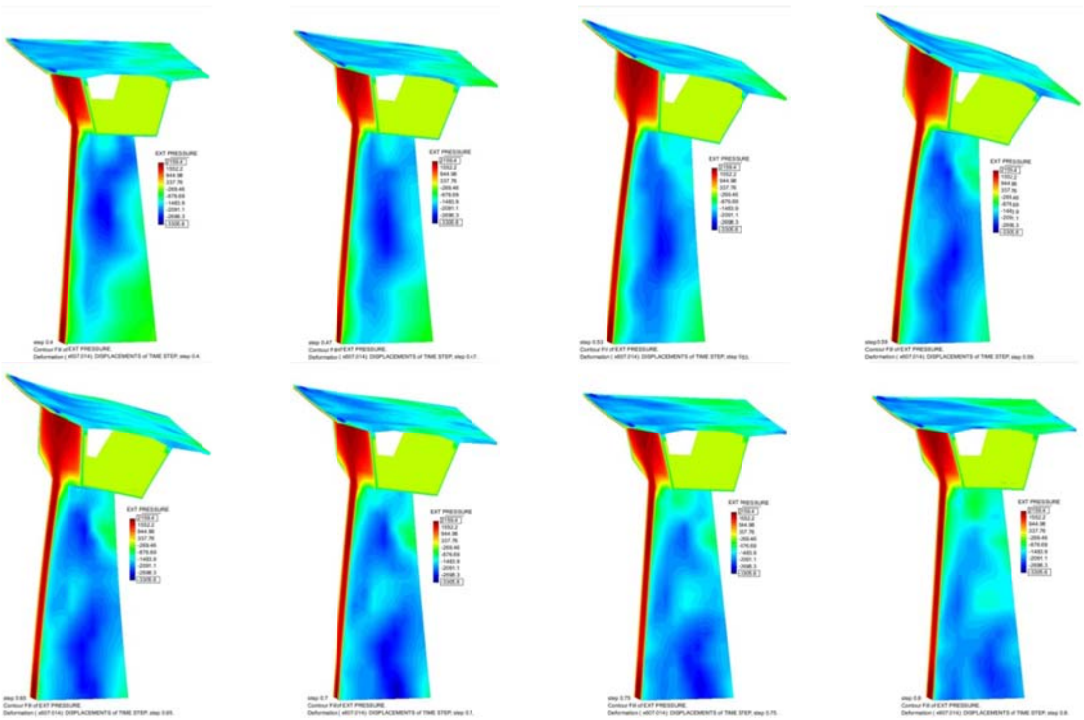

Figure 8 Wind pressures [Pa] and deformation variation in time for one cicle of wind induced vibration

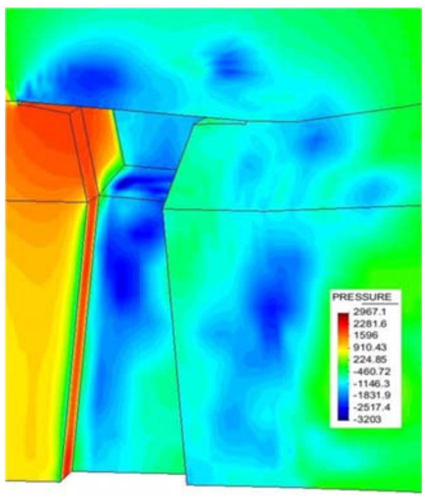

Figure 9 Fluid pressure [Pa] near structure

Table 1 Some maximum values obtained from Code and FSI analyses

Construction Stage	Top displacement (m)		Base shear (kN)		Overturning Moment (MN-m)	
	Code	FSI	Code	FSI	Code	FSI
5	0.0022	0.0083	1318.608	980.490	34.349	23.212

5 CONCLUSIONS

Result shows that static analysis derived of code requirements is a very conservative approach to estimate acting forces in initial constructions stages of analyzed bridge. This kind of approximate analysis is relatively easy to perform, but is maybe too expensive for this particular project. Analysis and comparative in final construction stages are necessary to determine security against wind action of the bridge, as well on complete constructed bridge.

6 ACKNOWLEDGEMENTS

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